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RESEARCH ON SOLID PROPELLANT COMBUSTION INSTABILITY

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ABSTRACT

Progress made during the third quarter of a research program directed toward a fundamental study of the non-steady combustion of solid propellants with application to rocket instability is described.

A polybutadiene-acrylic acid composite propellant containing 80% ammonium perchlorate and 2% copper chromite has been developed for use in conjunction with an oscillator-driver described previously. The operating characteristics of the oscillator system including the propellant and the motor have been defined over a useful operating range. Windows for the observation of processes within the motor have been tested but were found to become obscured too quickly. The system is currently being modified to correct this deficiency. An analysis of the decay of entropy waves in burnt gases produced in an oscillating pressure field indicates that the waves will persist for sufficient times to be observable.

I. INTRODUCTION

Previous reports in this series (1, 2) described the selection of techniques suitable for the study of the complex interaction of an oscillating pressure field with the flame of a burning solid propellant, which apparently lies at the heart of the solid propellant acoustic instability problem. In the last report (2) two experiments, a measurement of the temperature of the combustion gases downstream from the flame zone and the use of particle tracking for the observation of pressure-velocity relationships in the burnt gases, were described which appear to have the necessary sensitivity and pertinence. At the same time, a solid propellant oscillator-driver for the generation of high amplitude oscillations was designed and built.

This report describes the experimental determination of the operating characteristics of the oscillator-driver including propellant selection and dimensional optimization. Some preliminary experimental observations of the downstream temeprature profiles have been made and are described.

The persistence of entropy waves described earlier (2) is considered further in terms of a possible rapid decay by heat conduction. Analysis shows that this is not a problem in the pressure and frequency range of interest in this program.

II. DRIVER PROPELLANT SELECTION

The choice of a suitable driver propellant is the first step in obtaining high-amplitude oscillation from a rocket motor driver. Theoretical (3) and experimental (4) considerations indicate that highest amplitudes result from a high energy release rate, that is, from a rapid-burning "hot" propellant. This may be seen from:

$$\frac{\bar{N}}{\bar{p}} = \bar{m}/\bar{\rho}\,\bar{p} = (\bar{m}/\bar{p})(RT_f/M\bar{p})$$

so that:

$$\bar{N}/\bar{p} = \bar{m}/\bar{p}^2\,(RT_f/M)$$

The term $\bar{m}RT_f/M$ represents a heat release rate. The importance of the parameter lies in the fact that the acoustic admittance Y of the burning surface is given by:

$$Y = -\bar{N}/\bar{p} \times \text{(a response function)}\ ^{(2)}.$$

The more negative the value of Y, the greater the increase in the amplitude of a reflected pulse for a given incident pulse.

As a goal, an attempt was made to develop a propellant with a burning rate of at least 1 cm/sec. at 500 psi which could be readily prepared with suitable physical properties and castability. Accordingly, some test propellants were made in the solid propellant processing facility of the Guggenheim Laboratories, and their burning rates were determined in a strand burner. The polybutadiene-acrylic acid copolymer was chosen as binder because of its mechanical and processing properties, its chemical properties, such as oxygen content, and the fact that moderately high rates are obtained with ammonium perchlorate propellants using this binder (5). High oxidizer loading was desired, from the standpoint of both flame temperature and burning rate.

The first propellant tested contained 80% ammonium perchlorate, with a bimodal mixture, 70% unground and 30% fine (18μ). This mixture has been cast successfully into a number of ignition test motors. However, the burning rate was below one cm/sec. at 500 psi., the target rate. In an attempt to increase the burning rate, the coarse perchlorate was omitted, with the rates shown in Figure 1. The burning rate here was satisfactory, but casting properties were quite poor, since the mix was far too thick. Next, tests were run with fine perchlorate ground at 8000 rpm rather than at 12,000 rpm as previous, giving a mean diameter of 36 μ. Although the burning rate was acceptable, there were air holes in the resulting propellant due to the high viscosity of the mix.

At this point, the use of a burning rate accelerator was decided upon. The catalyst copper chromite was an obvious choice since this additive is a catalyst for ammonium perchlorate decomposition, and has previously been shown to effect a marked increase in the burning rate of ammonium perchlorate propellants (6). As a first test, 2% of the catalyst replaced the 36μ perchlorate with the result shown in Figure 1. It may be seen that a 50% increase in burning rate resulted. However, this mix was still too thick to be considered for motor use.

Due to the success of the copper chromite and the known castability of the bimodal perchlorate propellant, the next propellant cast contained 2% copper chromite added to the original 80% bimodal propellant. The resulting rates are shown in Figure 1. Once again, a 50% increase in burning rate at 500 psi resulted. The burning rate at 500 - .37 in/sec. 0.94 cm/sec. - was considered close enough to the target rate to be a candidate for the driver propellant, especially since castability was good.

III. DRIVER PARAMETER INVESTIGATIONS

A number of shots have been fired to investigate the operating parameters of the oscillator driver The frequency was

varied by using different motor lengths, and the amplitude of the oscillations was optimized by changing the length of propellant in the driver sections. All firings took place at approximately 500 psi average chamber pressure.

The results are shown in Table I.

TABLE I

Motor Length (in.)	Driver Length (in.)	Freq. (cps.)	Amplitude (psi.)
3 + 3	1 5/8 + 1 5/8	1600	20
3 + 3	1 1/2 + 1 1/2	1600	25
5½ + 5	3 + 3	1190	150
5½ + 12 + 12 + 5½	3 1/2 + 3 1/2	430	100
5½ + 12 + 12 + 5½	4 3/4 + 4 3/4	430	200
5½ + 12 + 12 + 5½	4 3/4 + 4 3/4	430	150
5½ + 12 + 12 + 5½	5 5/16 + 5 3/8	430	25
5½ + 12 + 12 + 5½	5 1/4 + 5 3/8	430	100
5½ + 12 + 12 + 5½	5 1/4 + 5 5/16	430	150

For example, a 5½ + 12 + 12 + 5½ motor length refers to an oscillator with two 5½" driver sections and two 12" spacer sections, while driver length 5 5/16 + 5 3/8 means that propellant lengths of 5 5/16" and 5 3/8" were used in the driver section.

On the basis of the initial results, it was decided to use 5" length propellant in the driver section, at least for the firings at 430 cps. Six firings have been made with this configuration, with large amplitude ($>$ 150 psi) oscillations resulting every time. The maximum amplitude attained thus far has been 300 psi. and in every case, the oscillations have persisted at a high amplitude level for 200 to 500 milliseconds. A portion of a typical Visicorder record is reproduced in Figure 2.

IV. PHOTOGRAPHIC OBSERVATIONS

Since the direct photographic observation of the reaction of the burning zone to oscillating pressure fields is a basic aim of the planned experiments, tests were run to obtain suitable windows. Hydrostatic tests showed that suitably fabricated windows of either Vycor or quartz would contain 3,000 psi.

Test firings were next made without a camera to test window materials under motor operating conditions. Again, both the Vycor and the quartz windows withstood the temperature and pressure without any untoward effects. Furthermore, both were quite clear after the shots, meaning that carbon deposition would apparently not present any problem.

Difficulties were, however, encountered when test samples were mounted on the motor end wall in the test section. Soot built up shortly after ignition, obscuring the windows and preventing observation of the gas column. Luminous zones were, however, visible in the short viewing time available, as would be predicted by the entropy wave hypothesis.

At the present time, a purge system is being installed, in an attempt to insure clear visibility throughout the firing. Further tests will be made upon completion of the purge.

V. PERSISTENCE OF ENTROPY WAVES

The fact that temperature waves in a gas in a duct would decay by heat conduction, might be a limiting factor in the observation of entropy waves. Accordingly, an estimate has been made of the effect of one-dimensional heat conduction on the persistence of the entropy waves.

Consider a gas column with an initial temperature distribution, assumed sinusoidal. For simplicity, regard the displacement from the mean temperature as the quantity to be investigated. Assume pure one-dimensional heat conduction, so that:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

with boundary conditions:

at $t = 0$ $\quad T = T_{max} \sin 2\pi x/L$

where $L = \lambda_p$, the particle wavelength,

and $T(0, t) = T(L, t) = 0$

The general solution of (1) is:

$$T(x,t) = \frac{2}{L}\sum_{n=1}^{\infty}\left[\int_0^L f(z)\sin(2\pi x/L)\,dz\right]\sin(n\pi x/L)\, e^{-\left(\frac{n\pi}{L}\right)^2 \alpha t} \qquad (2)$$

where $f(z) = \sin 2\pi x/\lambda_p \; T_{max}\, e^{-(2\pi/\lambda_p)^2 \alpha t}$

Using orthogonality of the sine function,

$$\int_0^L \sin 2\pi x/L \sin n\pi x/L \, dx \begin{cases} = 0 , & n \neq 2 \\ = \frac{L}{2} , & n = 2 \end{cases}$$

Therefore, equation (2) becomes:

$$T(x,t) = \sin 2\pi x/\lambda_p \, T_{max_i} \, e^{-(2\pi/\lambda_p)^2 \alpha t} \tag{3}$$

To investigate the persistence of the temperature wave, it suffices to observe the decay of the exponential term. Solving for the time when the amplitude is T_{max_i}/e ,

$$\tau = \left(\frac{\lambda_p}{2\pi}\right)^2 \frac{1}{\alpha}$$

As an initial estimate, take α = 1 cm^2/sec. This number is obtained by an extrapolation based on simple kinetic theory, from room temperature and pressure to T = 2700° K and p = 25 atm.

If we now assume λ_p = 1 cm, as in the film previously analyzed, τ = 25 msec. With an average velocity of 400 cm/sec, x=10 cm.

These values are for a frequency of 500 cps, so that the persistence is of the order of 10 times the particle wavelength and τ is over 10 times the period.

Two factors will change the magnitude of the characteristic time; τ/λ_p a measure of the frequency of oscillation, and α , which will vary with the pressure and temperature.

<u>At 100 cps</u>:

λ_p = 5 cm

τ = 625 msec - 60 times period

x = 250 cm - 50 times particle wavelength

<u>At 1000 cps</u>:

λ_r = .5 cm

τ = 6.25 msec - 6 times period

x = 2.5 cm - 5 times particle wavelength

In short, as the frequency increases, the persistence decreases, both absolutely and relatively.

The pressure effect is threefold:

i) gas diffusivity varies inversely with pressure.
ii) gas density varies directly with pressure.
iii) burning rate varies with pressure to some power less than one.

As an example, take $p = 10$ atmospheres. The diffusivity will increase to 6.25 cm^2/sec, while effects (ii) and (iii) will combine to raise the gas velocity to about 630 cm/sec, if an exponent $N = .5$ is assumed. As a result, for 500 cps,

τ = 4 msec - about 2 periods

x = 2.5 cm - less than 2 wavelengths

For a higher pressure, $p = 50$ atmospheres,

τ = 50 msecs

x = 14 cm

so that there is a definite increase in the persistence of the entropy wave with increasing pressure.

In short, it is only at low pressures and high frequencies that entropy waves will be expected to decay to isentropic conditions in distances of the order of a wavelength. Even further increases in frequency or decreases in pressure would be required before decay occurred in times and distances characteristic of the flame zone, at least on a heat conduction basis.

The values calculated above represent a sort of upper limit, since the effects of turbulent mixing, heat loss to the walls, and spatial irregularities help to smear out the entropy wave. However, they do indicate that low frequency measurements of the type planned here are feasible.

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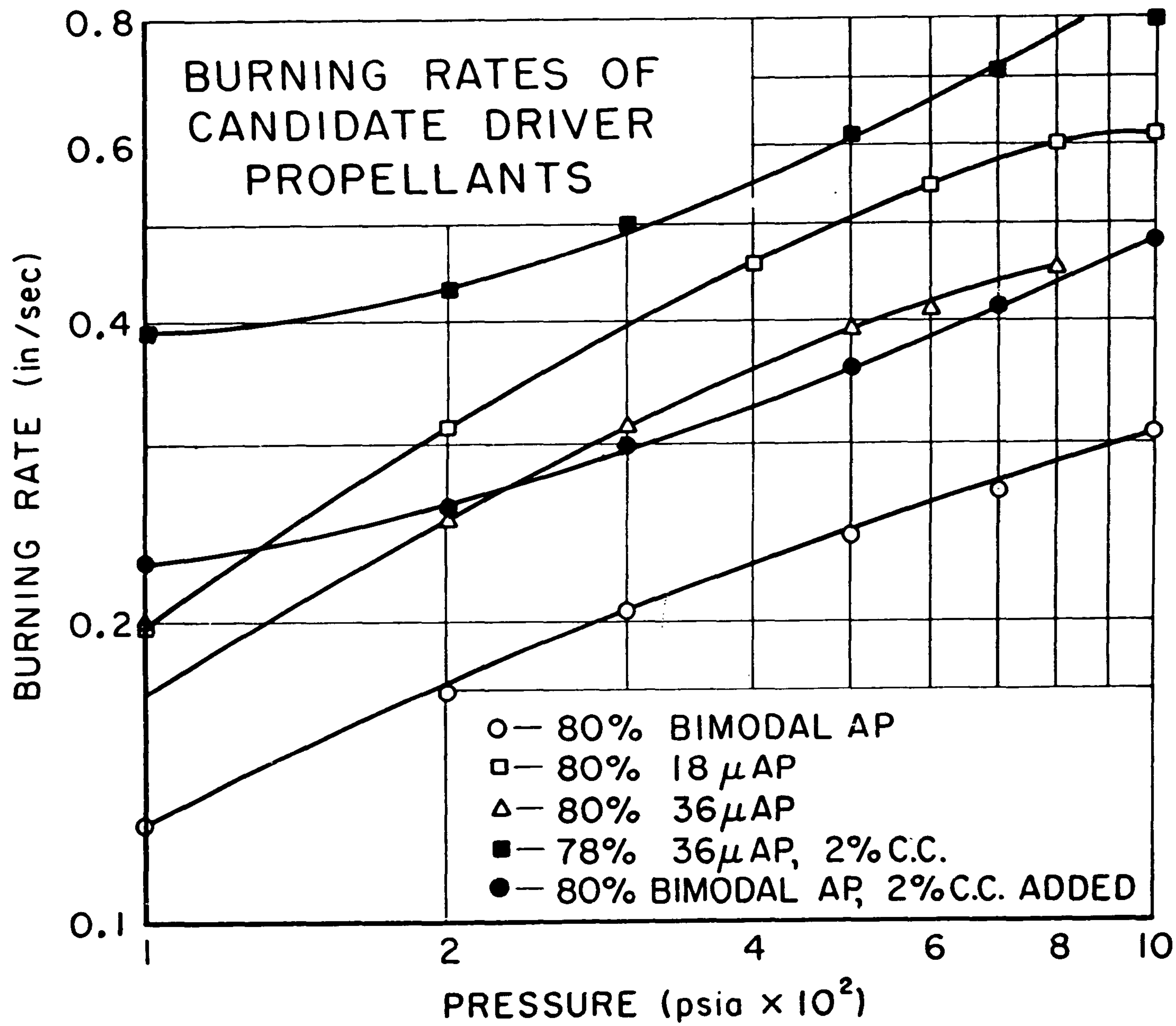
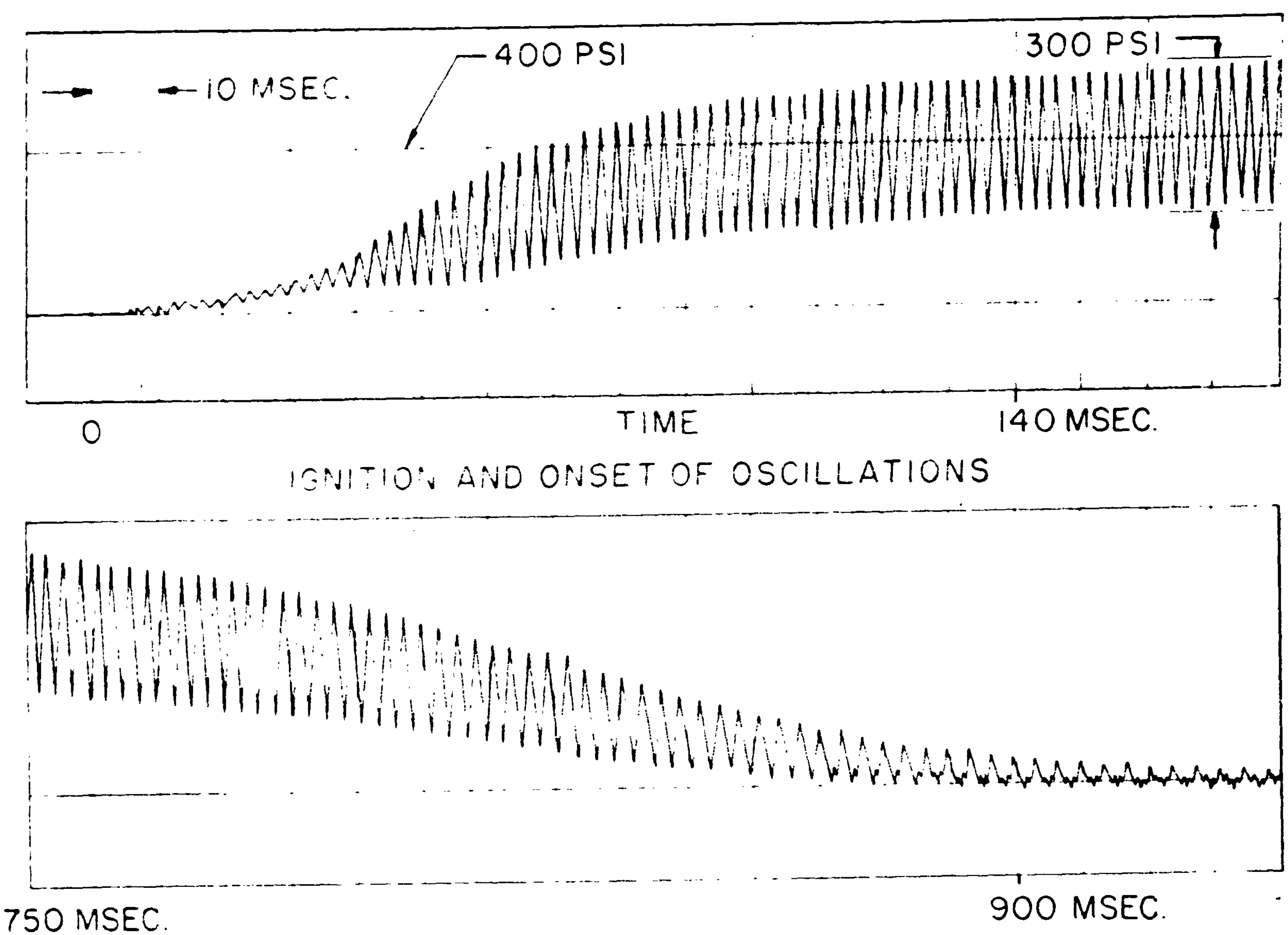

BURNING RATES OF
CANDIDATE DRIVER
PROPELLANTS
BURNING RATE (in/sec)
0.8
0.6
0.4
0.2
0.1
1
2
4
6
8
10
PRESSURE (psia × 10²)
○— 80% BIMODAL AP
□— 80% 18 μAP
△— 80% 36μAP
■— 78% 36μAP, 2% C.C.
●— 80% BIMODAL AP, 2% C.C. ADDED

FIGURE 1



VISICORDER RECORD OF OSCILLATOR DRIVER FIRING

FIGURE 2